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Soot removal from ancient Egyptian complex painted surfaces using a double network gel: empirical tests on the ceiling of the sanctuary of Osiris in the temple of Seti I—Abydos

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Abstract

In this study, we evaluated the ease of removal of soot layers from ancient wall paintings by employing double network gels as a controllable and safe cleaning method. The ceiling of the temple of Seti I (Abydos, Egypt) is covered with thick layers of soot; this is especially the case in the sanctuary of Osiris. These layers may have been accumulated during the occupation of the temple by Christians, fleeing the Romans in the first centuries A.D. Soot particulates are one of the most common deposits to be removed during conservation-restoration activities of ancient Egyptian wall paintings. They usually mask the painted reliefs and reduce the permeability of the painted surface. A Polyvinyl alcohol-borax/agarose (PVA-B/AG) double network gel was selected for this task since its properties were expected to be compatible with the cleaning treatment requirements. The gel is characterized by its flexibility, permitting to take the shape of the reliefs, while also having self-healing properties, featuring shape stability and an appropriate capacity to retain liquid. The gel was loaded with several cleaning reagents that proved to be effective for soot removal. Soot removal tests were conducted with these gel composites. The cleaned surfaces were evaluated with the naked eye, a digital microscope, and color measurements in order to select the best gel composite. The gel composite, loaded with a solution of 5% ammonia, 0.3% ammonium carbonate, and 0.3% EDTA yielded the most satisfactory results and allowed to safely remove a crust of thick soot layers from the surface. Thus, during the final phase of the study, it was used successfully to clean a larger area of the ceiling.

Keywords: Abydos, Egyptian wall paintings, Gel cleaning, Polyvinyl alcohol-borax/agarose double network gel, Soot

Introduction

Accumulation of soot layers on the ceilings and walls of ancient Egyptian tombs and temples is a very common phenomenon. In the Roman period, numerous isolated tombs and temples, dating back to the Pharaonic period, were inhabited by Christian hermits. When they suffered from persecution and economic pressure by the Romans, these sites served as shelters for them and consequently some of these pagan sites were turned into churches [1, 2]. As a result of that occupation, the wall paintings of these Pharaonic sites became begrimed with thick soot layers produced by the domestic activities of the new inhabitants (cooking, lighting, heating, etc…). Incomplete combustion of materials produces smoke which in return results in the formation of particles of carbon (soot). Soot is mainly composed of carbon particles in combination with an oily matrix. The particles of carbon are of ca.

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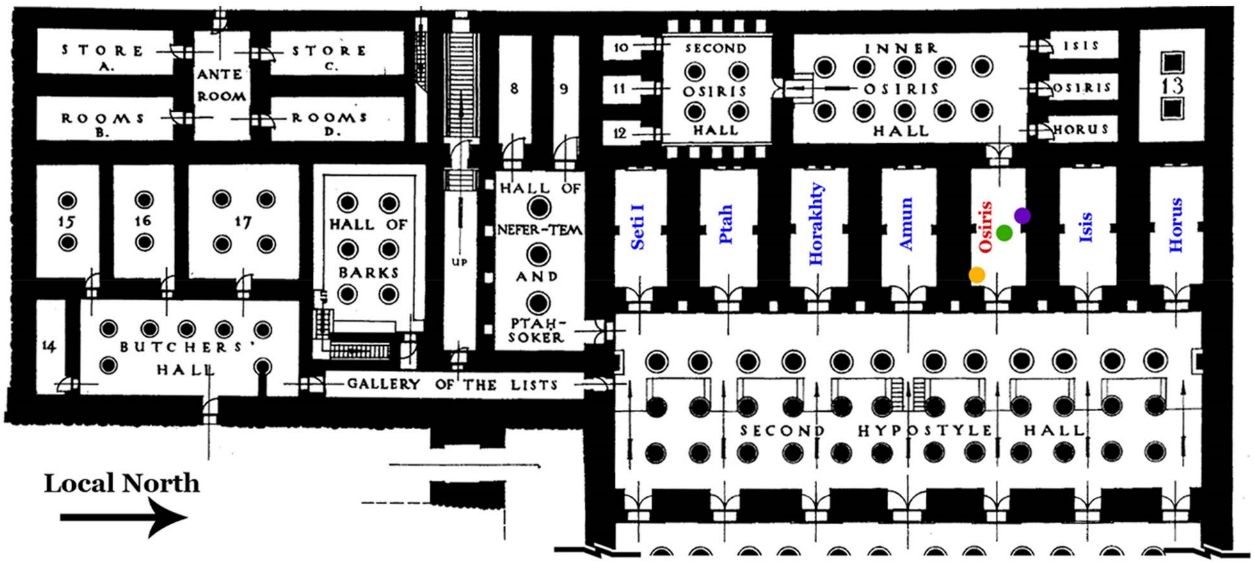

Fig. 1 Part of the plan of the temple illustrating the seven sanctuaries and the complex of smaller rooms behind the Osiris sanctuary; adapted from [13]. The color dots refer to the three areas where the gel cleaning tests were conducted (Green dot: 1st test, Purple dot: 2nd test, Yellow dot: 3rd test)

2.5 µm size and they form the visible soot agglomerations when they are attracted to each other by the oily materials [3–5]. In addition to the adsorption of various pollutants, these soot layers obscure the wall paintings and reduce the permeability of their surface [6, 7]. Moreover, conservators should consider safety requirements during the removal of these deposits as they can be irritant to the respiratory system or the skin [3].

In our study, cleaning tests were performed on the ceiling of the Osiris sanctuary in the temple of Seti I at Abydos, Egypt. The ceiling is covered with thick soot layers composed of carbon (C) as identified by means of XRD [8]. Seti I dedicated one of the seven sanctuaries in his temple to the god Osiris. Osiris is one of the most important and popular gods in ancient Egyptian history. This importance is derived mainly from two circumstances. The first one is that he suffered from a dramatic death: either by drowning or being murdered by his brother Seth. According to the myth, his corpse was dismembered, reconstituted and mummified by his wife Isis and his sister Nephthys. Isis, after becoming impregnated by the mummified Osiris, gave birth to a son Horus who was secretly raised by her to protect him from his uncle. Upon reaching maturity, Horus managed to triumph over Seth and was crowned king of Egypt. This myth is significant as it ensured Egyptians that they could survive after death. Secondly, Osiris was popular due to the fact that, after the victory of his son, he was installed as the ruler of the netherworld where every deceased Egyptian had to travel through for regeneration after death. The cult of Osiris was connected to Abydos (situated in Thinite province—upper Egypt) in addition to Busiris (situated in the east—central Delta) [9–12].

The sanctuary of Osiris is the most interesting one in the temple and is located in the middle of a series of seven sanctuaries devoted to different deities; see Fig. 1. All the sanctuaries contain false doors on their west side except for the Osiris sanctuary that has a real door. The latter leads to a complex of small rooms dedicated to the celebration of the Mysteries of Osiris.

The paintings of the temple of Seti I have been studied previously [8, 14–16]. They were performed by means of different techniques. In some cases, the stone (limestone and sandstone) was cut into sunk/raised reliefs or a combination of both, covered with a whitewash and then painted using the secco technique. While in other cases, the Egyptian artist applied a thin preparatory layer (composed of calcite, gypsum, and quartz) to the uncarved or carved stones. The pigments used were Egyptian blue, Egyptian green, red ochre, and yellow ochre. Gum Arabic was used as the binding medium for these pigments.

Numerous reagents have been used for the cleaning of soot particulates from artwork surfaces. They include solvents, salts, and surfactants [17, 18]. The most commonly used reagents are as follows: (a) solvents such as ammonia, ethanol, white spirit, acetone, trichloroethylene, and ethyl acetate, (b) surfactants such as orvus,[1]

[1] An anionic surfactant composed of sodium dodecyl sulphate.

vulpex[2], and triton X-100[3], and (c) salts such as sodium bicarbonate, ammonium carbonate, sodium carbonate, tri-ammonium citrate, and ethylenediaminetetraacetic acid (EDTA). Traditionally, they are used individually or in mixtures and applied by cotton swabs or poultices [3, 17–21]. As an example, in a recent study, Zn nanoparticles mixed with vulpex has been successfully used to remove soot, patches of waxes and blood from the wall paintings in the temple of Isis in Luxor, Egypt [7]. In another study concerning conservation-restoration of the mortuary temple of Ramses III in Luxor, enzymes have been used to remove soot deposits, blood of bats and a deteriorated varnish of animal glue applied as a protective coating in a previous conservation treatments [22]. An attempt to evaluate soot removal from acrylic emulsion paintings has been carried out using dry cleaning methods (commercial erasers, sponges, and homemade bread) and non-contact cleaning methods (atomic oxygen and CO_2 snow) in comparison with wet cleaning [5]. Water, homemade bread, and the so called 'Absorene sponge' were able to remove the soot without altering the treated surface. Agar gel has been tested for the cleaning of stone sculpted surface "Fuga in Egitto" high-relief of the Duomo of Milan [23]. The most effective results were obtained by using 3% agar loaded with 1% Tween 20% which was able to safely and easily remove the accumulated soluble salts and soot particles after one hour contact time.

In view of the previous literature survey, a few studies have been dedicated to study the removal of soot from painted surfaces in general and ancient Egyptian wall paintings in particular. In addition, traditional cleaning methods were employed in the soot removal procedures such as cotton swabbing and poulticing which have a number of limitations/disadvantages. In the case of thick soot layers, the use of cotton swabs embedded in the cleaning reagents is not recommended by conservators as it causes damage to the paint layers. This is because there is not enough contact time for the reagents to soften the soot and consequently the removal depends mainly on the mechanical action of swabbing. Moreover, the aggressive mechanical action embeds part of the soot particles further into the pores of the surface. In such cases, conservators usually use poultices composed of cellulose pulp, carboxymethyl cellulose (CMC), and the proper cleaning reagents mixed into water. These poultices permit long contact time for the reagents to soften the soot which can be removed later with cotton swabs. However, poultices cannot retain the liquids for relatively long time as they evaporate fast in elevated temperature. In addition, part of the liquids is absorbed by the porous surface which introduces more of the chemical reagents into the treated surface. Finally, in some cases the poultice may leave cellulose fiber and CMC residues on the treated surface [24, 25]. Due to the limitations posed by the traditional cleaning methods in the removal of soot from ancient Egyptian wall paintings, gel cleaning was proposed as an alternative cleaning approach to be tested for this task.

Gels are deemed to be controllable and safe cleaning method [26, 27]; thus, they were evaluated for removing thick soot layers from the ceiling of the sanctuary of Osiris (see Fig. 2a, b). In previous studies, we developed a polyvinyl alcohol-borax/agarose (PVA-B/AG) double network gel and studied its properties. It was tested to remove deteriorated consolidant layers from wall paintings of the same sanctuary and it was able to successfully remove the consolidant without damaging the paint layers [28]. In addition, we investigated the different characteristics of the PVA-B/AG double network gel. According to these investigations, the gel is characterized by the following features: (a) it is a flexible gel with the ability to adapt its shape to complex surfaces such as the case of ancient Egyptian painted reliefs, (b) it features good shape stability when applied on painted surface for extended contact times, and (c) it can be loaded with a wide range of reagents such as mixtures of polar and non-polar solvents, chelating agents, and surfactants, (d) and it has a good liquid retention, a relevant property required in sites characterized by elevated temperature and very low levels of relative humidity [29].

Based on the above-mentioned features, the PVA-B/AG double network gel was deemed suitable for cleaning tasks in the sanctuary of Osiris. For this reason, the gel was loaded with various cleaning reagents, already documented in literature to have the ability to remove soot particles. The prepared gel composites were applied to the ceiling of the Osiris sanctuary during two cleaning tests and the results were assessed visually and microscopically. In view of the difficulty of reaching the cleaning locations (vaulted ceiling ca. 4 m above floor height), the option was taken not to use other/more sophisticated (spectroscopic) characterization equipment on site to assess the difference before and after treatment. The most effective gel composite was adopted to treat a larger area of the surface as a final demonstration of its efficiency.

Methods and methods

Materials

Polyvinyl alcohol *(PVA)* (98.0–98.8% hydrolyzed, M.W. 146,000–186,000) and Ethanol 96% (technical) were acquired from Acros Organics. Disodium tetraborate

[2] An anionic soap composed of potassium methylcyclohexyl oleate.

[3] A nonionic surfactant composed of octyl phenol ethoxylate.

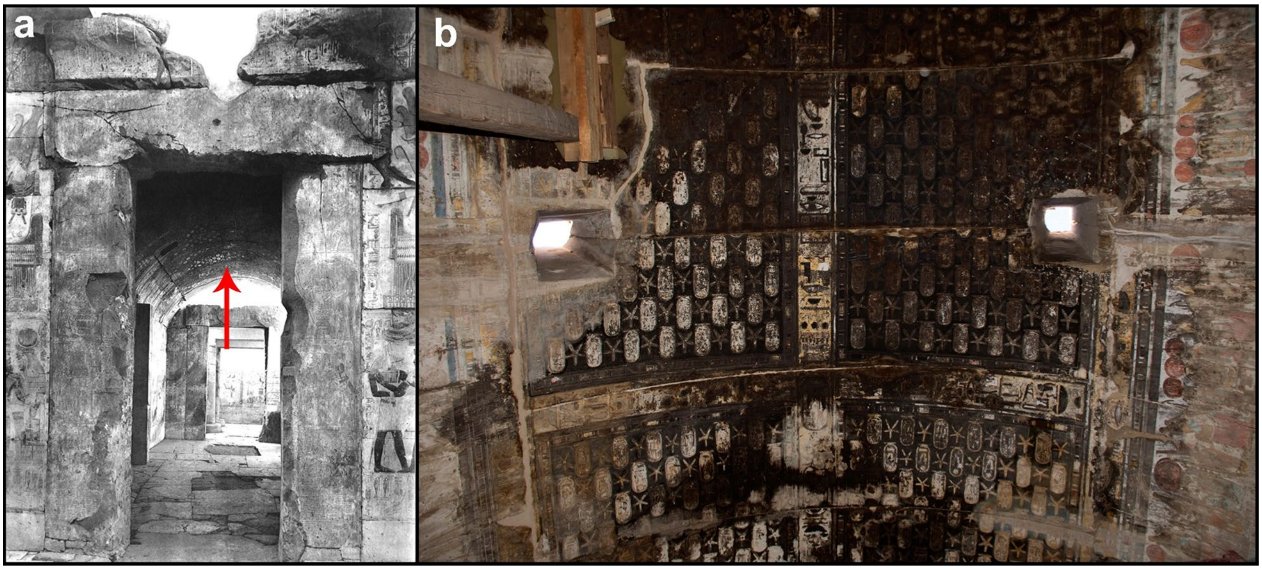

Fig. 2 **a** Black and white photograph from 1930s of the sanctuary of Osiris (looking to the West), showing the vaulted ceiling covered with black soot layers (red arrow) [13]. **b** Photograph of the painted ceiling of the sanctuary of Osiris, largely covered with soot

decahydrate (borax, ACS, ISO reagent), and Titriplex® III for analysis (EDTA, ethylenediaminetetraacetic acid, disodium salt dihydrate) were obtained from Merck. Agarose *(AG)* (molecular biology grade, low EEO/Multipurpose), dimethylformamide *(DMF)* (>=99%) and trichloroethylene were supplied by Fisher scientific. Acetone ≥ 99% (technical) was purchased from VWR chemicals. Sodium dodecyl sulfate *(SDS)* (purity 98%) and ammonium carbonate were obtained from Sigma-Aldrich. Ammonia solution 33% (pure reagent for analysis, M.W. 17.03) was acquired from ADWIC. Ethomeen® C25 was obtained from Kremer pigmente. Triton X-100 was acquired from Talas. Vulpex liquid soap was purchased from Diffher & Johnson.

Gel preparation

PVA-B/AG double network gel composites were prepared according to the procedures explained elsewhere [28]. The gel concentrations used for the first and second tests were 3% PVA, 1% agarose and 0.6% borax.

Strategy of cleaning tests

The damaged parts of the ceiling provided information about the structure of the paint layers. The ceiling is composed of sandstone slabs and the decorations were carved into raised reliefs. A whitewash was applied to the reliefs in order to receive the paint layers. The soot layers mask the majority of the ceiling especially its upper part (see Fig. 2b).

The goal of the cleaning strategy was to remove as much as possible of the soot layers without provoking damage to the paint layers underneath. The selected spots for the cleaning tests were homogeneously covered with thick soot layers. This was to allow formulating a good evaluation of the removal results. For this reason, the PVA-B/AG gel was loaded with cleaning reagents able to remove soot based on literature data; the concentrations of these reagents were adjusted to be compatible with the gel. For instance, the total concentrations of the salts (e.g. EDTA, ammonium carbonate, and SDS) was kept below 1% since high concentration of these salts causes excessive syneresis and makes the consistency of the gel to be much stiffer [29–31]. A day before the treatment, the gel composites were prepared, confined in Petri dishes and preserved in the refrigerator (5 °C). The main purpose of the prepared gel composites is to soften the agglomerations of soot. The gel composites, with good results, would require minimal swab action when they are removed from the surface. Aggressive mechanical action leads to damaging the paint layer and/or more penetration of the soot into the pores of the surface. The gel composites were applied to the surface for 45 min. The temperature and the relative humidity were measured, during the cleaning treatments, using an Optirion data logger (Opt 506H). The results were evaluated based on visual and microscopical examinations on the treated spots in addition to the ease removal of the soot. Color measurements (CIE-Lab color space) were performed on the photographic images representing the visual appearance of the cleaned spots with

Table 1 The six 3%/1% PVA-B/AG gel composites loaded with the selected reagents

Gel composites (GC)	Reagents	Concentrations in water (%)
GC1	Ammonia Acetone Triton X-100	5 (v/v) 5 (v/v) 0.5 (v/v)
GC2	Ammonia Ammonium carbonate EDTA	5 (v/v) 0.3 (w/v) 0.3 (w/v)
GC3	Ammonium carbonate EDTA	0.5 (w/v) 0.5 (w/v)
GC4	Trition X-100 EDTA	1 (v/v) 0.5 (w/v)
GC5	Acetone Ethanol SDS	5 (v/v) 1 (v/v) 0.7 (w/v)
GC6	Ammonia DMF	20 (v/v) 10 (v/v)

the gel composites. Following the criteria explained in [32], the L* a* b* coordinates were measured using Photoshop software for the uncleaned and the cleaned spots based on an average of 20 measurements for each spot. We focused on the L* coordinate for the evaluation of the black soot removal efficiency (white = 100 and black = 0). The difference in lightness: (ΔL*) = L*(cleaned spot)—L*(uncleaned spot) [33], higher values of ΔL* corresponding to a better cleaning efficiency. Finally, the most efficient gel composite was employed to clean a larger area of the ceiling of the sanctuary of Osiris.

Results and discussions

First cleaning test

Six cleaning reagents incorporated in the PVA-B/AG gel were evaluated in this test[4]; they are presented in Table 1. Gel composites GC2, GC3, GC4, and GC5 showed minor syneresis due to the inclusion of EDTA, ammonium carbonate, and SDS; the syneresis effect was higher in GC3 than that in gel composites GC2, GC4, and GC5. This syneresis can be described as a superficial liquid layer covering the surface of the gel piece (See Additional file 1: Fig. S1). Those gel composites were blotted on a tissue paper to remove any excess liquids before they were applied on the surface. More information on the gel composite stability over 30 days is presented in Additional file 1: Table S1 and Fig S2.

The six gel patches were applied directly on the blackened surface of the ceiling (see Fig. 3a) and gently pressed to adapt their shape to the structure of surface. The diameter of the circular gel patches was ca. 5 cm and had a thickness of ca. 3 mm. They were covered with

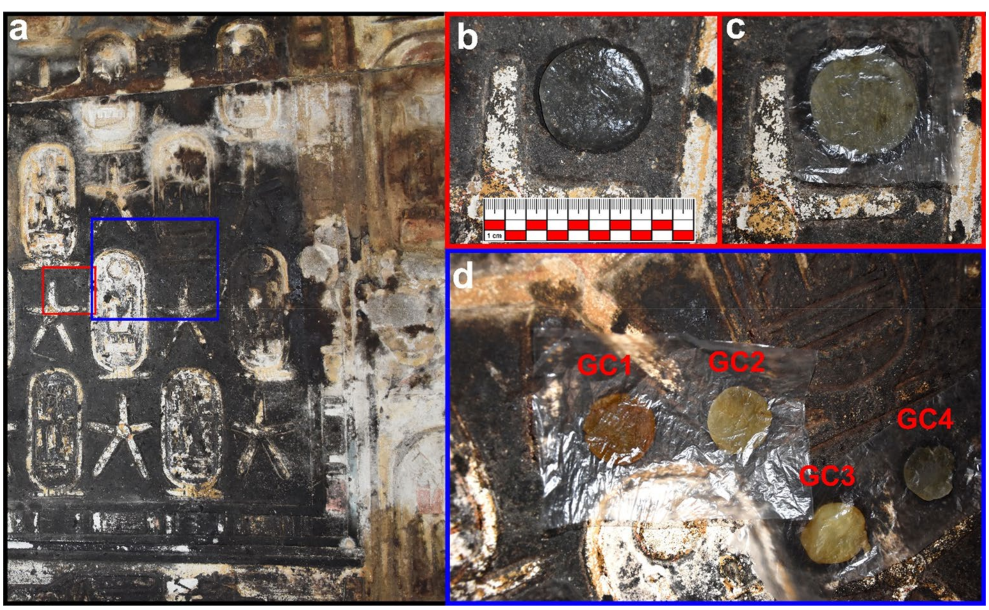

Fig. 3 Color changes in the gel patches after 30 min of application. **a** View of the surface selected for treatment. **b** Transparent appearance of gel patch GC5 (see red rectangle in **a**); few seconds after application. The scale bar represents 10 cm. **c** Changes to the color of the same gel patch after 30 min of application. **d** Color of GC1, GC2, GC3, and GC4 patches [inside blue rectangle in (**a**)] after 30 min of application; all gel patches are covered with polyethylene foil

[4] This test was carried out in April 2018.

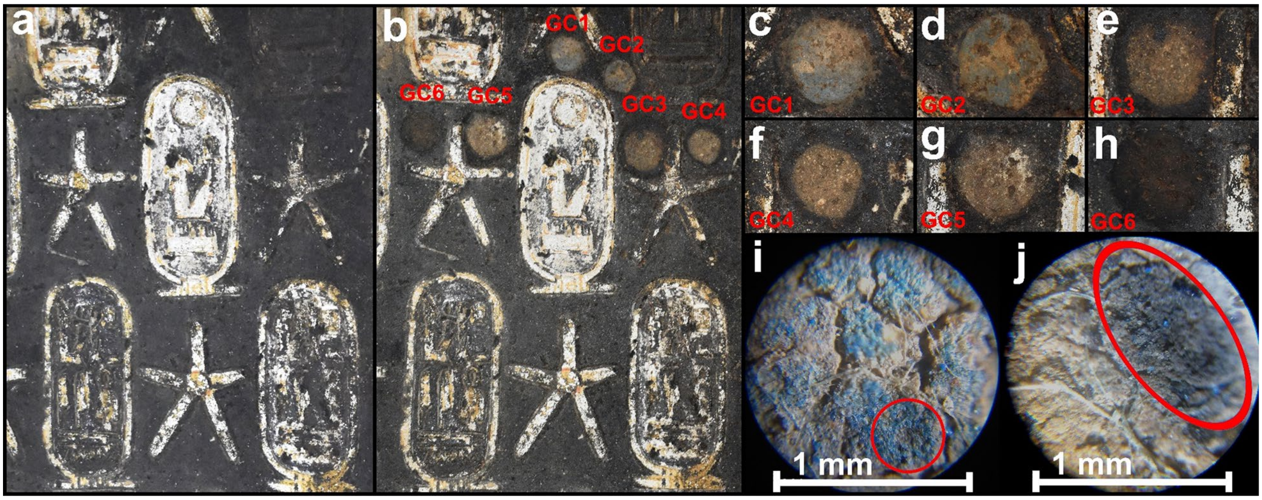

Fig. 4 **a** View of the selected area prior to cleaning. **b** The same view after treatment with 6 circular gel patches. **c**–**h** Close up view of the treated spots with the six cleaning composites. **i** Optical microscopy (OM) image of GC2 treated spot showing the blue paint layer almost free from soot deposits on the surface and in the cracks. The red circle refers to remainings of soot embedded in the paint. **j** OM image of GC5-treated spot, still showing the presence of soot on the surface after the treatment (indicated by the red oval)

polyethylene film to reduce the evaporation of the liquids. The color of the gel composites changed after several minutes of application due to the reaction with the soot deposits (see Fig. 3b-d). After approximately 45 min, the gel pieces were gently peeled-off. The gel composites removed some of the superficial loose soot agglomerations. Later, dry cotton swabs were gently rolled over the surface to remove the remaining softened soot agglomerations (see Additional file 1: Fig. S3). The temperature and relative humidity were 35 °C and 41% respectively during the treatment. Figure 4a, b shows photographs of the ceiling before and after treatment. Figure 4c-h illustrates the final visual results of the soot removal by the six gel composites. Visually and microscopically, GC1, GC2, and GC4 allowed to remove the thick soot layers and reveal the original surface underneath. GC3 and GC5 did not soften the soot layers adequately and the removal with the swabs was not easy. On the other hand, GC6 showed no noticeable change on the treated spot. Figure 4i, j shows the difference in the cleaning efficiency between spots treated with GC2 and GC5 respectively, under microscope. It can be seen that GC2 removed the majority of the soot layers while GC5 shows the presence of soot agglomerations on the surface. It is worth mentioning that the removal of the softened soot layers was easier with GC1 and GC2. However, it was difficult to perform color measurements and determine which was the best cleaning result due to the heterogeneity of the original surface: in some areas, the paint layers became detached prior to their soiling with soot. Thus, it was decided to perform more tests on other areas of the ceiling where the paint layer was still intact.

Second cleaning test

This test was performed on two areas of the North side of the vaulted ceiling of Osiris sanctuary[5]; one red painted oval area and a nearby rectangular area (originally painted blue). The selected spots to be treated were homogeneously covered with soot (see Additional file 1: Fig. S4). Due to the noticeable good results and the ease soot removal obtained by GC1 and GC2 in the first test, they were again employed in this test in addition to three other gel composites (see Table 2). The five gel patches, each with a diameter of ca. 4 cm and a thickness of ca. 2 mm, were applied on the two different areas using the

Table 2 The five 3%/1% PVA-B/AG gel composites employed during the second soot cleaning test

Gel composites (GC)	Reagents	Concentrations in water (%)
GC1	Ammonia Acetone Triton X-100	5 (v/v) 5 (v/v) 0.5 (v/v)
GC2	Ammonia Ammonium carbonate EDTA	5 (v/v) 0.3 (w/v) 0.3 (w/v)
GC3	Ethomeen C25	1 (v/v)
GC4	Trichloroethylene Vulpex	5 (v/v) 1 (v/v)
GC5	Ethomeen C25	5 (v/v)

[5] This test was executed in September 2018.

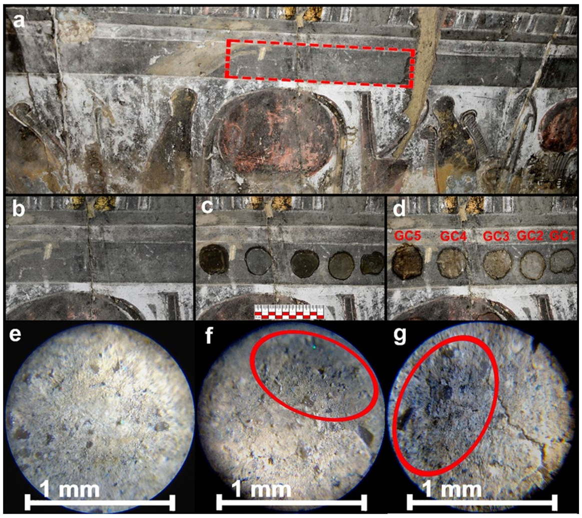

Fig. 5 **a** General view of the selected area for the test, **b** before treatment, **c** during application of the five gel composites, and **d** after treatment. The scale bar represents 10 cm. **e** Spot treated with GC2 under the microscope shows no noticeable soot deposits while **f** and **g** show residues of soot (indicated by the red ovals) on the spots treated with GC4 and GC5 respectively. All microscopic images were acquired at a magnification of 120 x

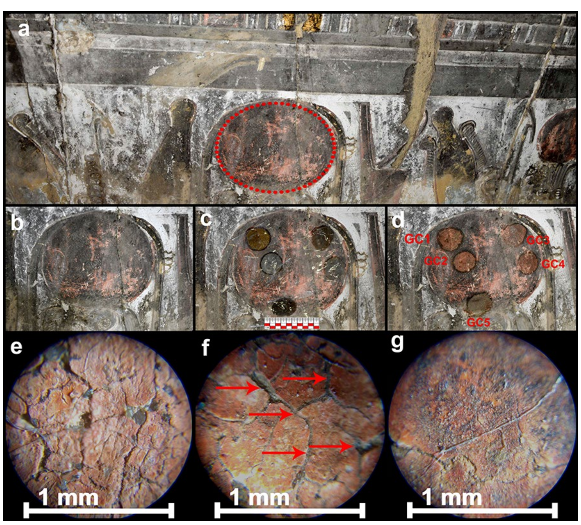

Fig. 6 **a** General view of the selected area for the test, **b** View of the red oval before treatment. **c** Five gel patches during application, covered with plastic sheets to reduce liquid evaporation. The scale bar represents 10 cm. **d** View after treatment. **e** OM image of the spot treated with GC2. The soot layer was removed from the painted surface as well as from the cracks. **f** Microscopic image collected from a spot treated with GC4. The arrows refer to the soot agglomerations entrapped in the cracks. **g** Microscopic image of the spot treated with GC5. Residues of the soot remain on the surface and in the cracks of the paint layer. OM magnification: 120×

same protocol as described above. The temperature and the relative humidity were 33 °C and 40% respectively.

This test offered more clear results than the previous one. By means of visual examination, it became obvious that GC2 allowed to homogeneously remove most of the soot layers from the two treated painted areas (see Figs. 5b–d and 6b–d). It is known that it is difficult to remove all the soot particles especially those fine ones trapped within the pores of the contaminated surface. GC2 succeeded in softening the soot layers and their removal with the dry cotton swab was easily done. The other gel composites (GC1, GC3, GC4, and GC5) were not able to sufficiently soften the soot layers to be removed by cotton swabbing and left inhomogeneous cleaned surface. It is worth mentioning that GC5 (loaded with 5% ethomeen C25) was less efficient than GC3 (loaded with 1% ethomeen C25) and also left behind an oily stain on the treated surface especially on the blue paint layer (see Figs. 5d and 6d). Using a portable microscope, it is clear that GC2 also effectively removed the majority of the soot deposits from the surface of the paint layers (See Figs. 5e and 6e). The other gel composites also removed the soot but in a less efficient manner. For instance, as shown in Figs. 5f, g and 6f, g, some soot deposits are still present on the surface and within the cracks on the spots treated with GC4 and GC5. The acquired ΔL^* showed that GC2 gained the highest values in the two treated areas (red paint and blue paint); indicating that it performed the best cleaning results. Furthermore, the ΔL^* values of the other gel composites reflected the lack of their cleaning efficiency (see Additional file 1: Table S2). Thus, based on the previous evaluating investigations as well as the ease removal of the soot, we can conclude that GC2 is the most efficient gel composite for the removal of soot layers in this specific context.

Third cleaning test

In this test[6], a large GC2-loaded gel patch was applied on an area of the ceiling of around 18×10 cm^2. The concentration of PVA and agarose was adjusted to be 4% and 1% respectively for the following reasons: (a) improve the workability of the gel, (b) increase its shape stability and (c) enhance the liquid retention to suit the elevated temperature in the archaeological site and to permit reuse of the gel. When the liquid retention property increases, this allows the gel not to lose the majority of the liquid and consequently retain enough of it for the second use. During this test, the temperature was 35.5 °C and the relative humidity was 30.5%. The gel was assembled piece by

[6] This test was executed in August 2019.

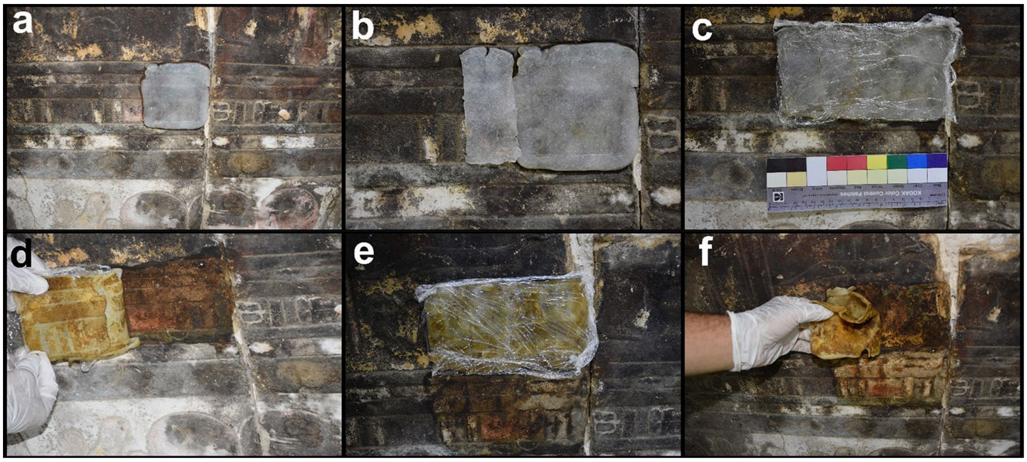

Fig. 7 **a**–**c** illustrating the assembling of the PVA-B/AG gel (loaded with 5% ammonia, 0.3% ammonium carbonate, 0.3% EDTA) covered with a plastic sheet. **d** Removing the gel after ca. 45 min. The gel self-healed into a single gel slab **e** Applying the other side of the same gel slab for the second treatment. **f** Removing the gel slab after the second treatment. It is noticeable that the gel adhered to the surface

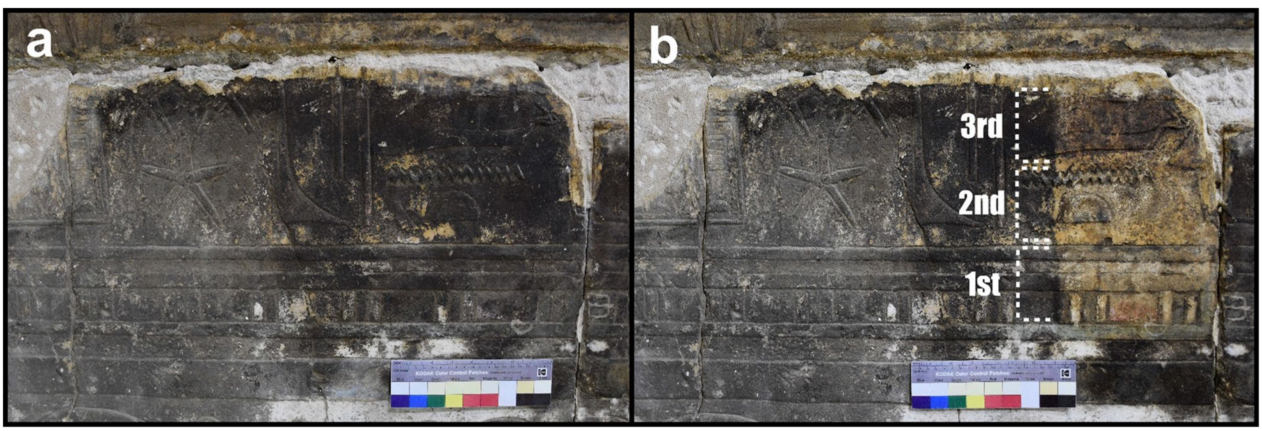

Fig. 8 **a** View of the selected area for the third test before the cleaning. **b** The same view after the first, second, and third treatment with the same gel slab. It is clear that the third treatment did not show as satisfying results as the first two treatments

piece on the surface to form a large single gel slab, by taking advantage of its self-healing properties (see Fig. 7a–c). Once applied on the surface, the gel was covered with a polyethylene sheet and peeled-off after ca. 45 min; as indicated in Fig. 7d. It was obvious that the gel conformed to the structure of the reliefs on the ceiling and removed part of the deposited soot while softened the rest. Thus, the softened residual deposits could be easily removed with dry cotton swabs. As such, similar results could be drawn during the second test regarding the suitability of the GC2-loaded gel for soot deposits removal.

The same gel slab was then reused two times on nearby locations; the results are summarized in Fig. 7e, f). Unfortunately, the gel suffered from cohesive fracture and left residues behind on the surface when peeled-off in the second and third cleaning treatments (Fig. 7f). This can be ascribed to the absorption of an important part of the gel liquid by the highly porous and dry surface which in return lead to a decline in the mechanical properties of the gel and it became brittle. In the third cleaning trial, the cleaning efficiency noticeably decreased (see Fig. 8a, b).

Conclusions

In this study we evaluated the possibility of cleaning the soot-soiled ceiling of the sanctuary of Osiris in the temple of Seti I at Abydos, Egypt by means of a PVA-B/AG double network gel patches. For this reason, the gel was loaded with several cleaning reagents. Most of the PVA-B/AG gel composites tested allowed to remove the soot layers to different degrees in the first and second cleaning tests. In none of the cases, the underlying paint layers were affected. Based on the cleaning efficiency evaluation, the gel loaded with 5% ammonia, 0.3% ammonium carbonate, and 0.3% EDTA allowed to remove most of the soot agglomerations easily from the surface as well as from the cracks of the paint layers without causing any noticeable damage. It is worth noting that the concentrations of the above-mentioned cleaning reagents are very low compared to those loaded in the poulticing methods which makes the gel a safer method. In a third test, the above-mentioned gel composite was used to clean larger area of the ceiling of the sanctuary (ca. 18×10 cm^2). In addition, we evaluated the possibilities of reuse of the same gel slab for extra two times. The results were satisfactory during the first two treatments while the results of the third repeat treatment were less. However, after the second and third surface treatments with the same gel slab, it adhered to the surface and left residues during peeling-off. This suggests a decline of the mechanical properties of the gel that can be ascribed to the excess absorption of part of its liquid by the porous surface.

Regarding the PVA-B/AG double network gel, it could be successfully loaded with variable types of cleaning agents ranging from polar/non-polar organic solvents, salts, and surfactants. These reagents can be loaded individually or in combinations. However, the concentration of some of these reagents should be adjusted to be compatible with the gel such as when salts and non-polar solvents are loaded to avoid excessive syneresis to the gel [28, 30, 31]. The PVA-B/AG double network gel proved to be flexible enough to adapt to the structure of the complex surface of the reliefs. By regulating the concentrations of the PVA and agarose in the double network, it was possible to create gels with flexibility and liquid retention suitable for the cleaning needs of the case study. The self-healing character of the gel allowed for an effortless application of the gel to the surface in small adjacent pieces that healed within a few minutes to form as single large slab. The reuse of the gel depends on the porosity of the surface to be cleaned. When the porosity of the surface is low, the gel would not lose too much of its liquids which makes it suitable for another application. In case of strongly absorbing porous surfaces, reuse of the gel is not recommended.

The results presented in this work can serve as a model for future soot removal that would be conducted in the other sanctuaries of the temple. Furthermore, they can be applicable to other cases; however, conservators-restores should always implement pre-tests in advance to regulate the proper gel formulation and contact time that suit the wall painting to be treated.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-020-00473-1.

Additional file 1. Additional tables and figures.

Abbreviations

PVA-B: Polyvinyl alcohol-borax; AG: Agarose; EDTA: Ethylenediaminetetraacetic acid; SDS: Sodium dodecyl sulfate; DMF: Dimethylformamide.

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Authors' contributions

EA designed the strategy for gel cleaning tests and prepared the gels as well as he wrote the first draft of the manuscript. AM carried out the field tests. KJ and JC contributed to the strategy of the research as well as writing and revising the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All the data are available within the manuscript.

Competing interests

The authors declare that they have no competing interests.

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